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The Application of Cognitive Work Analysis to the Australian Collins Class Submarine

ABSTRACT

Australia's Defence Science and Technology Organisation (DSTO) is investigating the use of the Cognitive Work Analysis (CWA) methodology as a tool for the management of technological change, as well as in its more common role in interface and information support design. This paper describes a pilot study that has been carried out into the application of CWA to the command and control of the Royal Australian Navy Collins class submarines. A comprehensive work domain analysis has been completed, and sufficient progress has been made on control task analysis to demonstrate the ability of CWA to capture a multi-faceted, holistic view of a highly complex domain. Work is proceeding, not only towards the design of general and context-specific information support at the watch leader level of the command team, but also in using the insight gained about the functionalities of the submarine to map the results of new technology introduction. Initial results and interest among our Defence clients show promise that the methodology can be developed to produce some of the tools necessary to go forward.

INTRODUCTION

Very few complex systems compare to an operational submarine for the sheer variety of forms that this complexity can adopt. Submarines have now been operated for over a century, and the methods developed to deal with this complexity are under pressure as a result of developments in operational doctrine and tasking, as well by the continued development of sensor suites. Improved sensors and networked communications systems promise to widen the operating horizon of a submarine both qualitatively and quantitatively. However this gain is at the cost of greatly increased data volume which in turn places increased pressure on command teams and the systems that they use to develop and maintain tactical situation awareness.

To deal effectively with these issues requires a concept of the human as well as technical components of complexity. A useful definition is provided by Vicente (1999a) who defines system complexity in terms of: large problem spaces; dynamic behaviour; unpredictable coupling of system component behaviours; high hazard levels; uncertainty of information; mediated interaction with the environment; vulnerability to external, unanticipated disturbances; spatial distribution of operations; social and organisational behaviours and requirements; heterogeneous perspectives of workers within the system. A modern submarine, such as the Australian Collins class, typifies all of the above; with the last three becoming increasingly important as the concept of network centric warfare is developed and implemented.

Apart from the operational aspects of the Collins class submarines, societal and demographic factors are causing personnel retention and recruitment difficulties. Also, increased awareness of safety issues is generating a desire to place fewer personnel in harm's way. Overall, then, there is considerable pressure upon the submarines to perform more complex operations in more complex environments with fewer people. This, in turn, is driving a need to provide improved decision support tools for submarine command teams. It is also providing greatly increased impetus to the improvement of information processing and management systems. Such development generates its own problems in terms of change management and the accurate estimation of the appropriateness and effects of any such changes.

In response to these circumstances, Australia's Defence Science and Technology Organisation (DSTO) is investigating the use of the Cognitive Work Analysis (CWA) methodology as a tool for the management of technological change, as well as in its more common role in interface and information support design. The ability of CWA to capture a multi-faceted, holistic view of highly complex systems makes it a good candidate for the range of applications under investigation. It is against this background that a pilot study has been carried out in the application of the Cognitive Work Analysis methodology to the command and control functions of the RAN Collins class submarine.

THE COGNITIVE WORK ANALYSIS METHODOLOGY

The Cognitive Work Analysis (CWA) methodology was developed from studies into the safe operation of complex industrial systems. It was originally targeted at nuclear power plants, but has since been applied to a variety of other domains (Rasmussen, Pejtersen & Goodstein 1994). The methodology holds to the premise that it is impossible, for a sufficiently complex system, to identify all the future states that the system might adopt, either by its own operation or in response to external disturbances. This implies that information support and interface design based on predictions of possible system behaviour will at best be incomplete, and at worst can lead operators to make inappropriate or even dangerous decisions. The same argument can be made against attempting the full automation of such systems because of the danger of the system entering a state that is outside the defined parameters of control. Such an undefined state may result in control responses that are inappropriate or even hazardous.

CWA recognises that effective control of complex sociotechnical systems can only be achieved by means of creative problem-solving on the part of the system's operators and it seeks to assist such adaptability by the provision of appropriate information support. Because system complexity makes it impossible to uniquely specify correct operator responses to all possible system-states, some other basis must be found to guide operator actions. In CWA, this guidance is obtained from identifying behaviour-shaping constraints that will limit, but will not usually specify, the actions of operators or of automation. Such constraints tend to be invariant over a broad range of contextually-grouped system-states, and can thus be used as a basis for the design of an information support system that will support operators in responding correctly to unfamiliar situations that may not have been anticipated by the analysis and design process. The overall goal is to maximise the context-conditioned variability of response of the operators by providing them with appropriate interfaces to the system under control, and the general process by which this is achieved is known as Ecological Interface Design (Vicente 1999b; Vicente & Rasmussen 1992).

CWA Component Analyses

To identify the different forms of constraint on operator actions, CWA provides an integrated, multi-faceted framework for the work analysis of complex systems. Five different component analyses are specified, and the framework organizes them into an ecological perspective, commencing with the physical nature of the entire work domain and then progressively moving inwards to the cognitive processes of the operators (Rasmussen 1992). The five component analyses are listed and briefly described below in the order in which they are carried out:

Work Domain Analysis (WDA)

This analysis investigates the system to be controlled within its environment and examines the entire work domain in terms of a purpose-related means-ends hierarchy. The work domain is deconstructed in terms of both abstraction and physical decomposition and the analysis allows inspection of how the overall functional purposes of the system are ultimately linked to (and afforded by) the physical components that comprise it. The links take the form of chains of affordances and constraints that identify and connect functionalities at varying levels of abstraction, and the output from the analysis is an abstraction-decomposition hierarchy that captures this information. The structure and content of the abstraction-decomposition hierarchy provide a complete mapping of the areas of knowledge that a system operator might require as he or she focuses on different areas of the work domain, each at different levels of abstraction and/or decomposition during the cognitive processes that underlie decision making.

Control Task Analysis (CTA)

This takes the form of a constraint-based input-output analysis that permits identification and examination of prototypical cognitive subroutines that expert operators use in sequence to construct contextually appropriate responses to the system-states that they encounter. This analysis tends to take a high-level approach and concentrates on identifying what must be done, rather than a detailed description of precisely how it is to be achieved. The overall intention is to identify and support prototypical cognitive subroutines in order to make them more readily available for selection by the system operators, and a standard template known as a decision ladder is used to identify the cognitive subroutines used by expert operators, together with the cognitive trajectories that individual operators construct in reacting to work situations or in carrying out work functions.

Strategies Analysis

Having examined where control is to be carried out (work domain analysis) and what tasks are undertaken within it (control task analysis), this phase of the methodology identifies and examines how individual control tasks might be carried out. There is generally more than one method of carrying out a given cognitive task, and all such identified strategies should be supported in the design of any information support.

Socio-Organisational Analysis

This examines the division and coordination of work, and the social organization that controls how the various operators or actors communicate with each other. At this stage it is possible to examine how tasks and responsibilities are allocated to human actors and/or automation; the constraints that this may place on their behaviour; and the way that this will affect the information support requirements of each.

Worker Competencies Analysis

The final phase of the CWA methodology investigates the capabilities, both individual and generalised, of the human operators of the system to be controlled. On an individual basis, having identified and allocated responsibility for individual control areas and tasks, it is now possible to identify requisite operator capabilities and then use this information to specify selection criteria and training requirements.

On a generalised basis, CWA makes use of an empirical taxonomy of human cognitive behaviour to distinguish three overall categories: rule-based behaviour; skill-based behaviour; and knowledge-based behaviour. These three modalities require operators to interpret information in particular ways which require individual support. This information can thus be used directly in determining the form of information support or interface design.

LIMITATIONS ON THE STUDY

The pilot study described here was carried out to develop familiarity with the CWA methodology, and to gain some confidence in its applicability to the submarine command and control work domain. Because of this, limitations were imposed on project duration and resources. In turn, a severely restricted form of CWA was decided upon, in that most of the effort was to be spent developing a work domain analysis that concentrated on the tactical command and control aspects of the Collins class submarine. Once this was completed, the remaining resources were to be utilized in carrying out a control task analysis of one or two prototypical work situations or functions. It was expected that some strategies analysis information would emerge during the control task analysis, but it was not expected that a full strategies analysis would be carried out on the identified control tasks. No attempt was to be made to carry out a socio-organisational analysis, and only the general behaviour taxonomy was to be used to inform any initial attempt at information support design.

In the event, the work domain analysis was successfully carried out, as was a control task analysis for one prototypical work situation; that of returning the submarine safely from deep water to periscope depth (with no track history assumed in order to highlight aspects of tactical picture building). As expected, a small amount of information was collected on different strategies to be supported, but this was not expanded on by direct analysis. The final outcome was in the form of a table of information and knowledge-processing support that could form the basis of a context-sensitive interface screen design for the particular work situation analysed.

WORK DOMAIN ANALYSIS (WDA)

The work domain to be analysed was considered to comprise two separate interacting systems; the environment, and the submarine itself. Unlike earlier work in the naval command and control domain (Burns, Bryant & Chalmers 2000; Chalmers, Burns & Bryant 2001) contacts were not analysed separately, but surface vessels, subsurface vessels and aircraft were considered to be a part of the environment system to ensure that affordances provided for detection, classification and tracking (in terms of their effects on the environment) were captured. These two systems were then separately analysed at the five levels of abstraction commonly used for work domain analysis, here listed in decreasing order of abstraction: Functional Purpose; Priorities and Values; Purpose-Related Functions and Processes; Physical Functions and Capabilities; and Physical Objects/Resources.

The Environment System WDA

No functional purpose was allocated to the Environment system, and its WDA was thus limited to the lower four levels of abstraction.

The highest level identified, that of Priorities and Values, consists of the conservation laws of mass and energy that ultimately govern all large-scale physical interactions within the environment. These are invariant across the entire system, and provide absolute constraints on system behaviour.

The Purpose-Related Functions and Processes concern the processes by which mass and energy are transmitted through the environment. Thus they are concerned with the physical laws and constraints that govern such processes as surface wave generation and propagation, and the generation and propagation of light, acoustic, magnetic and electromagnetic radiation signals. Also captured at this level of abstraction are the laws that govern the physical movement of water and air masses that constrain the behaviour and structure of the large scale features of the oceans and the atmosphere.

The level of Physical Functions and Capabilities captures those aspects of the environment that are the direct effects of the influences and properties of the physical objects that comprise it. Examples of this are; the ability of solar radiation and air temperature and movement to affect the density of the surface layer of the ocean, and the ability of aircraft, surface and subsurface vessels, and marine life to generate various types of acoustic signals. This level is of particular relevance to the current study because it provides a complete listing of the affordances that a submarine can make use of to learn about its environment. This then provides a baseline required information set, against which to judge the effectiveness and completeness of the submarine's sensor suite.

The lowest level of abstraction, that of Physical Objects/Resources, consists of those major subsystems that form the environment with which the submarine interacts. As previously noted, these include aircraft and surface and subsurface vessels, as well as the physical components of the environment such as the ocean and its marine life, the atmosphere, the ionosphere and the planetary body itself, together with the Sun and the Moon responsible for tidal and climatic effects. The shape of the resulting abstraction hierarchy is shown below in Figure 1.

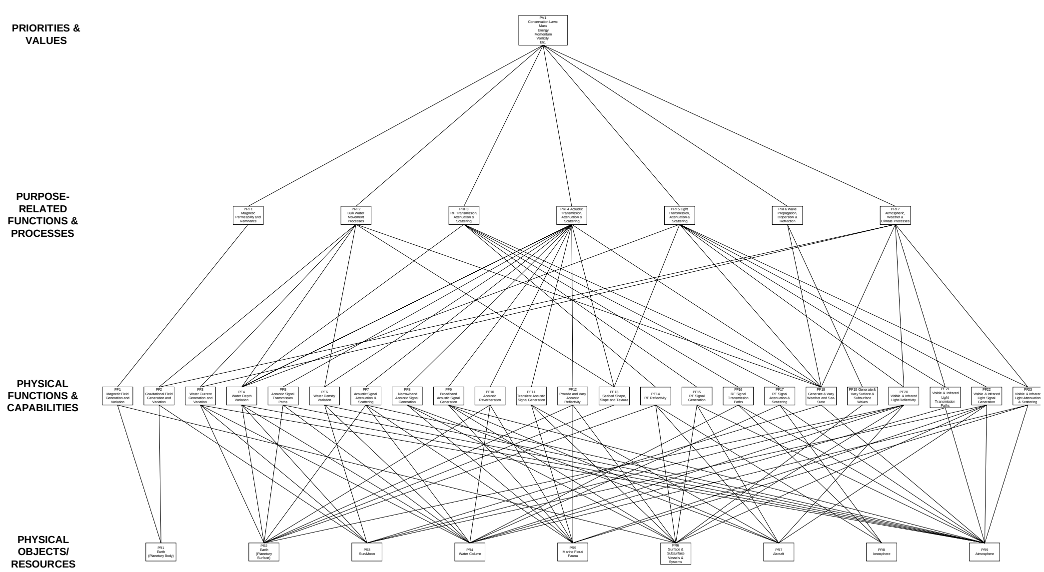

FIGURE 1. Environment System Abstraction Hierarchy

The Collins Class Submarine System WDA

This analysis was initially based on a wide range of documentation, ranging from high-level doctrine and mission statements, down to descriptions of individual systems and equipment found on board the Collins class submarines. The initial analysis took a relatively high-level viewpoint and concentrated on identifying the functionalities of the submarine as a whole. As a result, the physical decomposition was initially restricted to identification of those broad subsystems that were identified as providing the physical functions and capabilities of the submarine.

Once the submarine had been analysed as a component system of the work domain, attention was then refocused onto its subsystems. Analysis of these commenced by identifying their functional purposes to be the physical functions and capabilities previously identified for the high level submarine system. Subsystems were then physically deconstructed down to the level of individual function units (such as an individual sonar array, for example), and WDAs were then carried out for individual subsystems using the same levels of abstraction used for the overall systems, but at this finer level of physical decomposition.

The end result is a system-of-systems approach that allows the analyst to trace the chain of affordances and functionalities that links an individual function unit to the overall functional purposes of the submarine. The resulting abstraction-decomposition hierarchy is shown below in Figure 2.

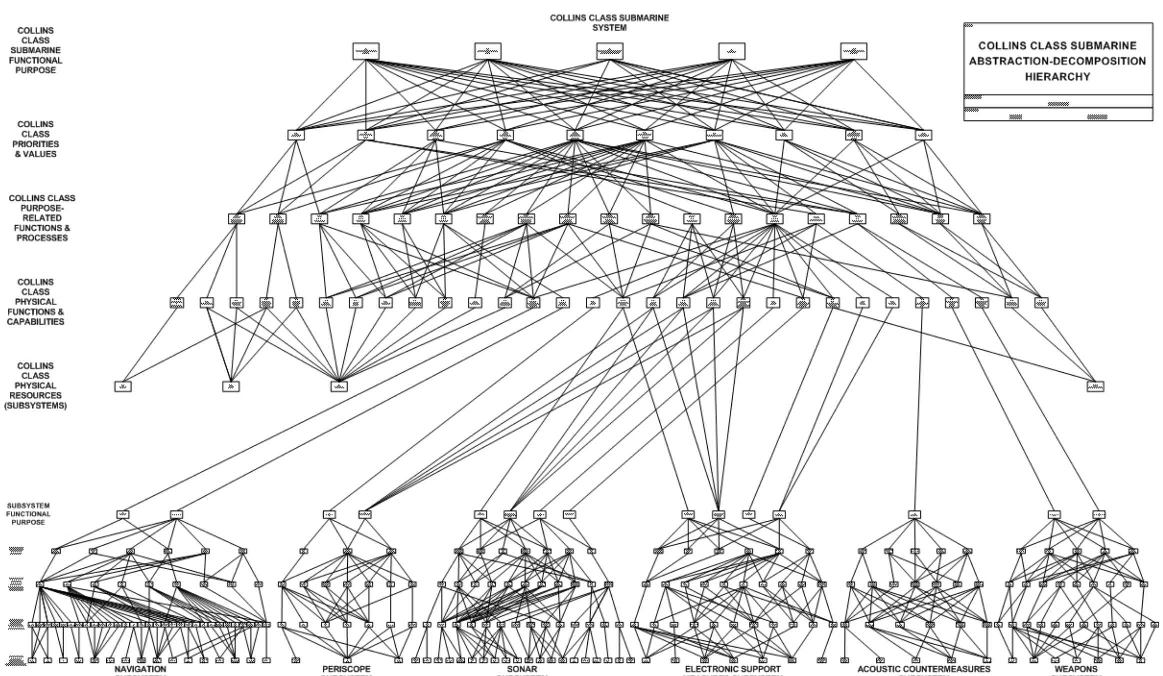

FIGURE 2. Collins Class Submarine Abstraction-Decomposition Hierarchy

The individual subsystems identified were: Training, Stores, Engineering, Navigation, Periscope, Sonar, Electronic Support Measures (ESM), Acoustic Countermeasures, Weapons, and Communications. To husband resources, four of the subsystems have been treated as “black-box” as far as immediate tactical command and control are concerned. This assumption will be tested in any future work to ensure that any further required analysis is identified and carried out.

On completion of the analysis, the abstraction hierarchies were presented at interviews with a number of subject matter experts (SMEs) for checking and validation. The current status of the abstraction hierarchies derived to date is that they appear to have achieved a high level of accuracy and completeness.

One of the aims of this study was to provide a stand-alone abstraction-decomposition hierarchy that could be investigated for alternative uses, possibly by others. To this end, a formal glossary was developed to define the identified functionalities more closely than the limited labelling on the diagrams would permit. This information, together with the developed abstraction hierarchies has been imported into a web-publishable database to provide a readily accessible user interface to the information. The interface will permit the user to view the hierarchies at a range of scales, rapidly trace out the means-ends links between the various identified functionalities, and to zoom in on individual functionalities to inspect their definitions and properties. Work is still under way on this project, and the intention is to publish it for on-line access within the Australian Defence Force intranet.

CONTROL TASK ANALYSIS

Once the WDA had been completed to the level described, the focus of the analysis was changed to the next phase of the CWA methodology; that of control task analysis. Available resources dictated that only a limited form of this analysis could be undertaken, and it was intended to examine a very limited subset of the prototypical work situations or functions that might occur during a submarine mission. To this end, a number of preliminary interviews were carried out to identify work situations that pose a high level of cognitive difficulty to operators and have the potential to place the submarine at considerable risk if errors are made.

One of the identified work situations; that of returning the submarine safely from deep water to periscope depth, was then selected for further analysis. Examples were also given at interview where the cognitive loading on the operators had been greatly increased by either the presence of multiple surface vessel contacts, or by the fact that equipment failure or the sound velocity/depth profile had made it impossible to maintain tactical situation awareness while deep. Accordingly, these two criteria were included in the description of the prototypical work situation to be analysed.

Three interviews were carried out, two with serving Lieutenant-Commanders and the third with a recently retired Commander. Total interview time was approximately 14 hours. All three interviews followed the same procedure. The interviewee was first asked to break the task situation into a temporal sequence of readily separable subtasks with no limitations placed on how many subtasks could be nominated. Alternative sequences of these tasks were identified, where possible, together with the reasons that might cause the operator to switch from one sequence to another. An example of such a task breakdown is shown in Figure 3 below.

Each of the identified subtasks was then examined in turn in order to investigate the cognitive decision-making processes of the interviewee, who was encouraged to recount actual experiences, rather than fall back on more generalised standard operating procedures. All information was documented onto the Rasmussen decision ladder template, and the sequence of decision ladders pertaining to the tasks identified in Figure 3 is shown below in Figure 4. Note that control task #2 is used twice.

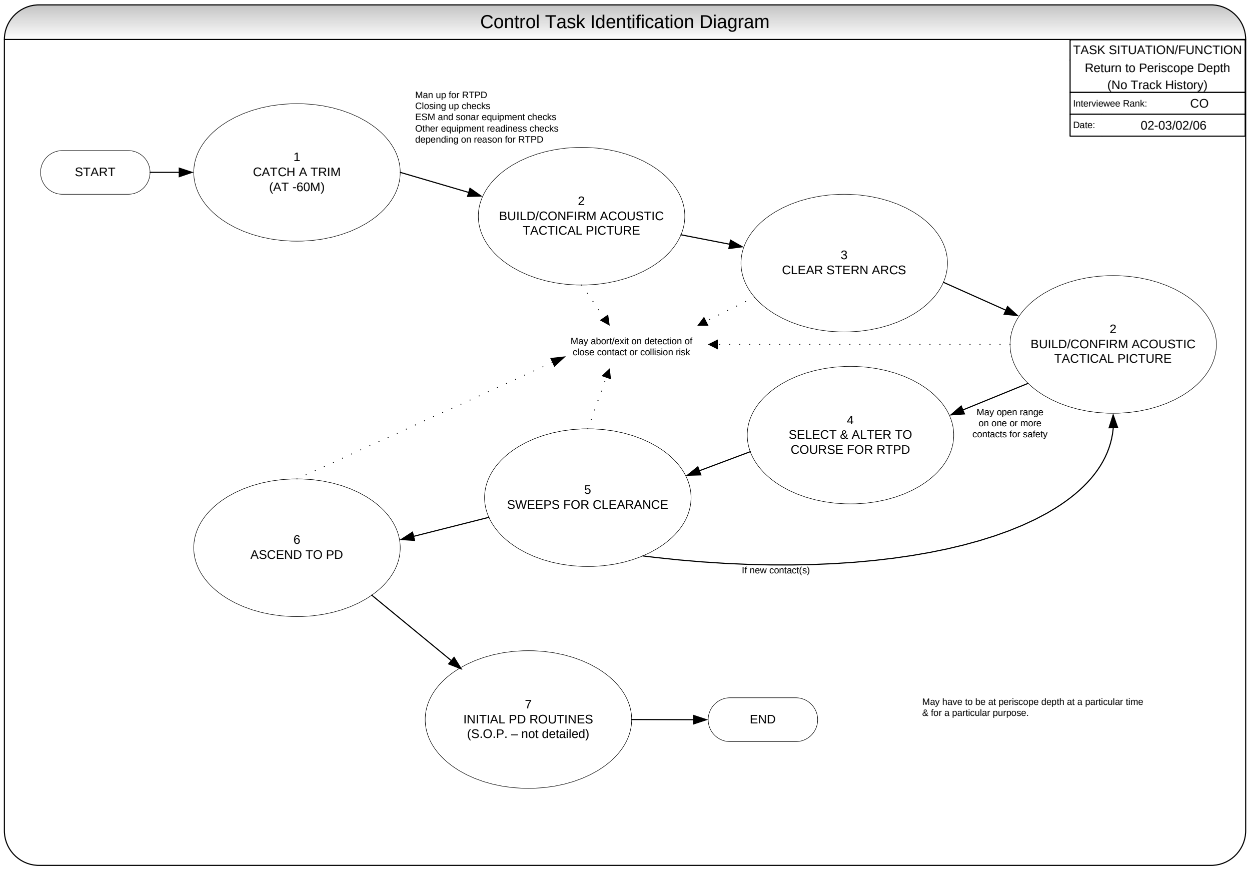

FIGURE 3. Control Task Identification Diagram

Inspection of the Figure 4 will show that each decision ladder may be considered to be a sequence of information processing activities (rectangular boxes) separated by states of knowledge (circular boxes). Every identified cognitive process was probed for details of the necessary information input, the knowledge outcomes, and the rules or constraints that governed the information processing activity that transformed the first into the second. Wherever possible, expert behaviour in the form of cognitive shortcuts and shunting paths (between knowledge states, and between information processing activities and knowledge states, respectively) was identified and documented.

The final outcome from this phase of the methodology was a listing (compiled across all interview data) of potential information content and knowledge processing support that might form the basis of information support design for the watch leader position during the single work situation examined.

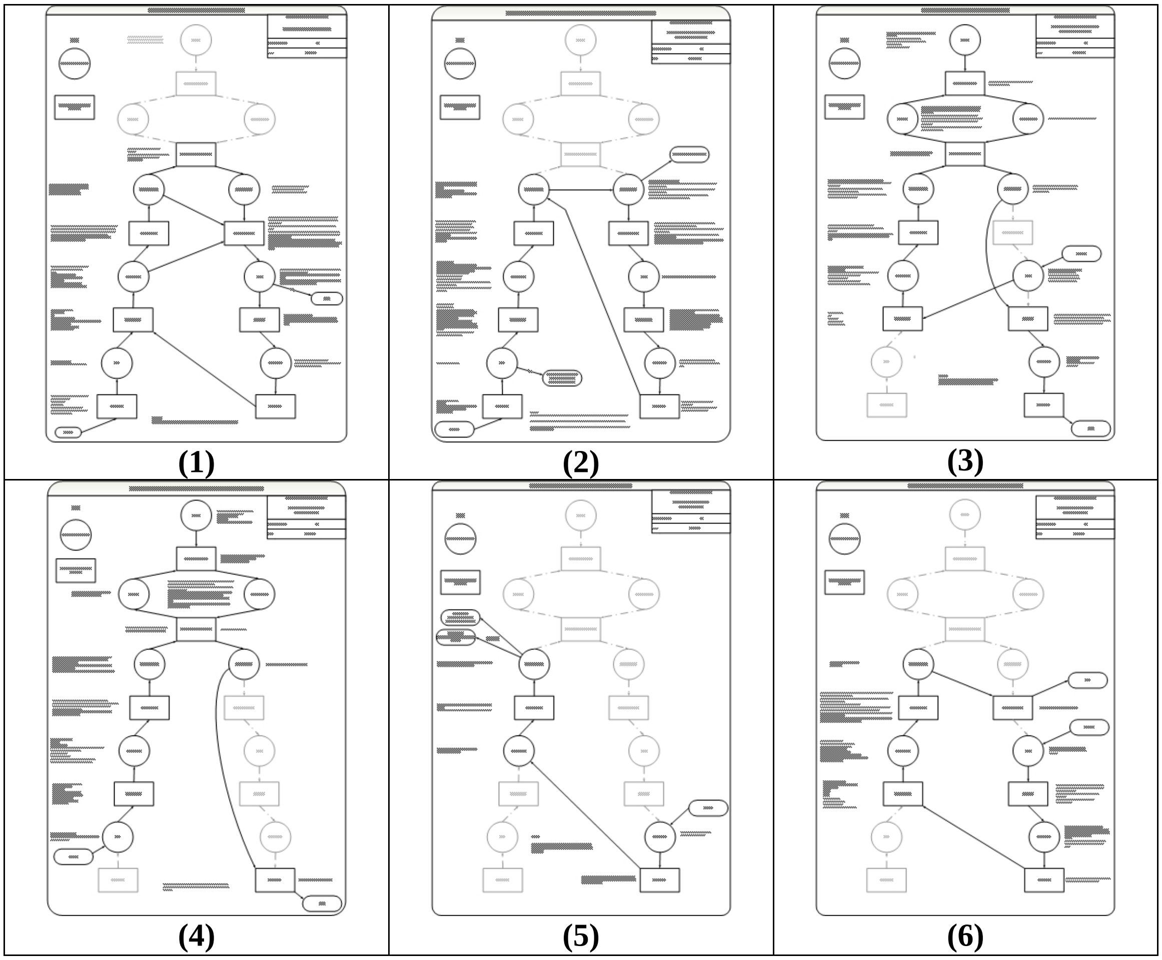

FIGURE 4. Decision Ladder Sequence

ONGOING WORK

Cognitive work analysis is currently being considered for application to a number of different aspects of the operational management of the Collins class submarines. These will be briefly described.

Improved Operator Interface and Decision Support Design

It is intended to continue the analysis of the command team functions using the full set of the CWA component analyses. Initially, the watch leader position will be further investigated across a range of work situations to design both general purpose and context-specific information support. These designs can then be subjected to simulation-based testing to quantify any performance improvements gained and to continue to build confidence in the methodology.

Given that one of the ultimate goals of this research is to reduce personnel numbers without compromising performance, the application of CWA will then need to be broadened to include the cognitive processes of the other members of the command team as it is currently structured. This much larger data set will then form the basis for an investigation into alternative team structures that make effective use of novel and improved forms of information support. Ultimately, back to back comparison of the original and revised command teams and interfaces using scenario-based simulations will be required to quantify any improvement gained.

Estimating the Impact of Technology Change on Submarine Functionality

The advent of the marine Automatic Identification System (AIS) has provided an opportunity to use the WDA results to map the effects of introducing new technology and capability on the functioning of the Collins class submarines. The abstraction-decomposition hierarchy allows for the mapping of affordance changes and investigations are being carried out into the allocation of measures of performance (MOPs) to the identified functionalities. The intention is to move towards a formalised, objective assessment framework that will provide tools for change management and for options comparison. It is intended to investigate the use of the hypertext-based WDA data to provide a mapping tool to visualise the effects of equipment or functional change. Such information could then be used to bring design outputs into closer alignment with user needs. More generally, tools arising from this research might also have application in the fields of risk assessment and reliability engineering.

Assistance in Managing the Future Development of Submarine Combat Systems

The combat systems of the Collins class submarines will shortly be replaced by a variant of a current US system, and future development will be undertaken in tandem with US submarine upgrades. However, the USN has no direct equivalent to the Collins class submarine and its particular capabilities. Because of this, it will be important to ensure that successive upgrades (largely driven by USN requirements) are appropriate to the tasking and functionalities of the Australian submarines, to identify areas where proposed upgrades might be inappropriate, and to recommend changes when required. This will require the ability to accurately compare the functionalities, tasking and operating methods of the US and Australian submarines and to identify differences that must be taken into account by any proposed combat system upgrade. As a first step to achieving this capability, work has commenced on the WDA of a USN SSN to be directly compared to that of the Collins class.

CONCLUSION

A pilot study into the application of cognitive work analysis to the command and control of Australian Collins class submarines has been successfully completed. Although primarily targeted at operator information support and interface design, initial indications are that the depth and richness of the information captured by the methodology may have application across a range of broader management aspects; some of which are already being investigated.

Sufficient confidence in the methodology has been established to continue the research, and the direction of future work is currently being discussed. It is likely that this will initially lead to the design of both general and context-sensitive information support for the watch leaders of the submarines. DSTO is developing the capability to carry out scenario-based simulation testing of command team processes, and the intention is to use this to quantify any performance gained from using our initial information support tools. Successful outcomes will result in the extension of the complete CWA methodology to the full range of command team functions and the subsequent examination of alternative team structure and information support combinations.

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